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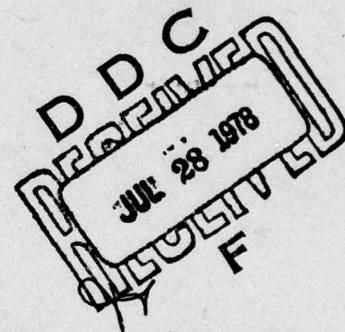
RADC-TR-78-140
Final Technical Report
June 1978



A SUMMARY OF REQUIRED INPUT PARAMETERS FOR Emitter MODELS IN
IEMCAP

Dr. Clayton R. Paul
University of Kentucky

Dr. Donald D. Weiner
Syracuse University



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ROME AIR DEVELOPMENT CENTER
Air Force Systems Command
Griffiss Air Force Base, New York 13441

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) The Intrasystem Electromagnetic Compatibility Analysis Program (IEMCAP) requires the inputting of various parameters to describe the emitter ports' emission spectra. This information is contained in the IEMCAP User's Manual (RADC-TR-74-342) but is not presented in a very concise manner. This report has summarized the required parameters and their measurement units. Along with this information the form of the power spectral density and suggested frequency table input values, to adequately represent the spectrum, are (Cont'd)		

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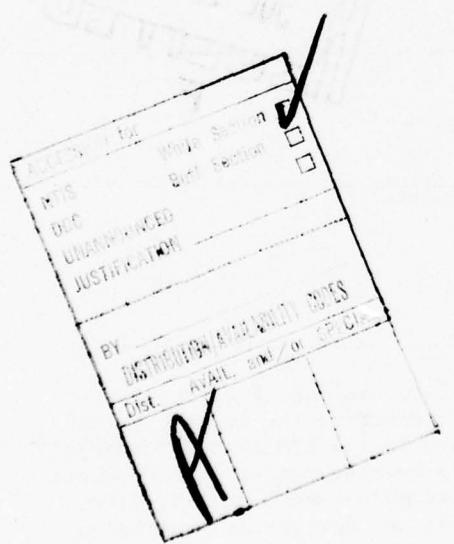
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presented. This information will simplify the effort needed to model an
emitter port.



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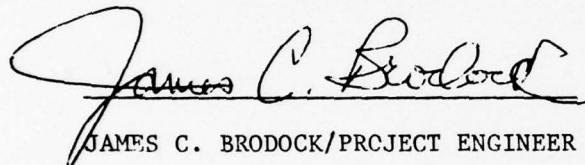
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The authors would like to acknowledge the capable efforts of Mr. Alan Oslan, Ms. Holly Race and Ms. Pam Nash of RADC who derived the entries in the frequency table for each model.

Evaluation

The Intrasystem Electromagnetic Compatibility Analysis Program (IEMCAP) is quickly becoming the most used EMC analysis tool to analyze the intrasystem compatibility of Air Force systems. In order to make the program easier to use, this report has summarized, in a short document, all the data necessary to describe the emitter ports in an IEMCAP analysis. This information will be used by the EMC engineer responsible for performing the IEMCAP analysis. This effort is in support of TPO R4C, Electromagnetic Compatibility.



A handwritten signature in black ink, appearing to read "James C. Brodock". The signature is fluid and cursive, with a long horizontal stroke on the left and more vertical and horizontal strokes on the right.

JAMES C. BRODOCK/PROJECT ENGINEER

I. Introduction:

The purpose of this document is to provide a summary of some of the important data input parameters for the emitter models in IEMCAP (Intrasytem Electromagnetic Compatibility Analysis Program). Two types of emitter models will be considered: Signal/Control Line Models and RF Models. The program contains models for other emitters (Power Lines, Electro Explosive Devices and Equipment Cases).

The format of this summary will consist of a time-domain picture of a typical signal followed by the definitions of the required input parameters in terms of the time-domain parameters.

For Signal/Control Line Models and RF Models, certain frequency parameters in the input data define the required frequency range for the port associated with the model. Over the required frequency range, the spectrum is defined by the appropriate model (stored in the code) and is not adjustable by the program. Over the remaining frequency range the spectrum is defined by the (user selected) MIL-STD limit, e.g. MIL-STD-461, and these spectra may be adjusted by the program for compatibility.

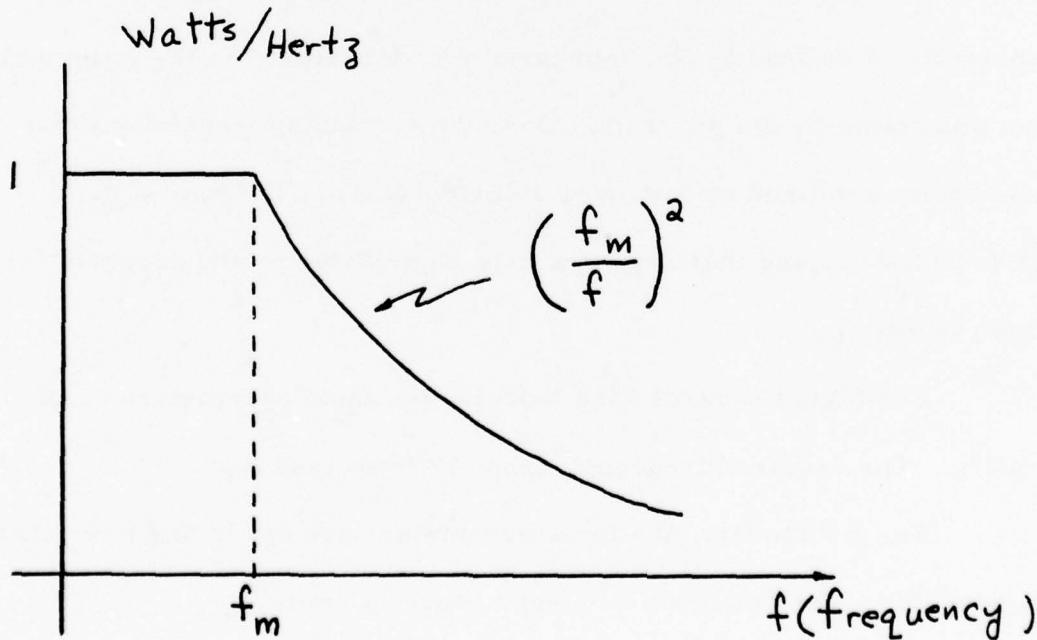
For Signal Control Line Models, the input parameters are f_l and f_h . The required frequency range is from f_l to f_h .

For RF Models, the input parameters are f_l , f_h and bwc (channel bandwidth). The required frequency range is from

$$f_l - \frac{1}{2} bwc \rightarrow f_h + \frac{1}{2} bwc$$

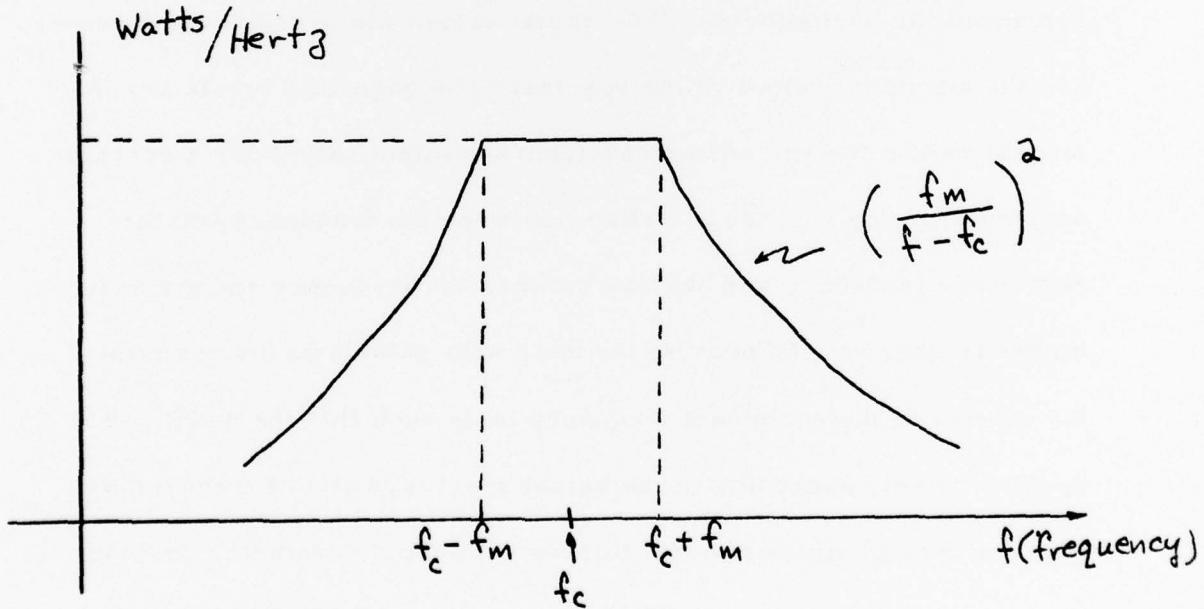
To provide the user with guidelines for selecting these parameters, the following criterion was chosen. The required frequency range was chosen such that the area under the power spectral density curve (as stored in the code) within this range is at least 95% of the total area under the curve. This criterion is reasonable since receptors respond to the total power within their passbands. For proper system operation, we should therefore attempt to insure that the major portions of the desired transmissions of the emitters are not designated as unrequired (and therefore adjustable).

As an example, consider the Signal/Control Line Models (PDM, NRZPCM, BPPCM, PPM, RECTPL, PAM) which have power spectral densities (which we have normalized to a peak value of unity) of the form



The total area under the curve can be shown to be $2f_m$ by straightforward integration from $f = 0$ to $f = \infty$. The area under the curve between $f = 0$ and $f = kf_m$ can be shown to be $(2 - 1/k)f_m$. Selecting k such that 95% of the area under the curve is between $f = 0$ and $f = kf_m$ yields a value of $k = 10$. Therefore f_l and f_h were selected as $f_l = 30$ Hz (the program only considers frequencies down to 30 Hz) and $f_h = 10f_m$.

For the RF versions of these models where the above Signal/Control Line waveforms amplitude modulate a carrier of frequency f_c , the power spectral density curves (again normalized to a maximum amplitude of unity) are of the form



Applying the above analysis of the Signal/Control Line Model to this and disregarding the fact that the curve does not go to zero at $f = 0$ as it does at $f = \infty$, we obtain for the required range $20f_m$ (twice the required

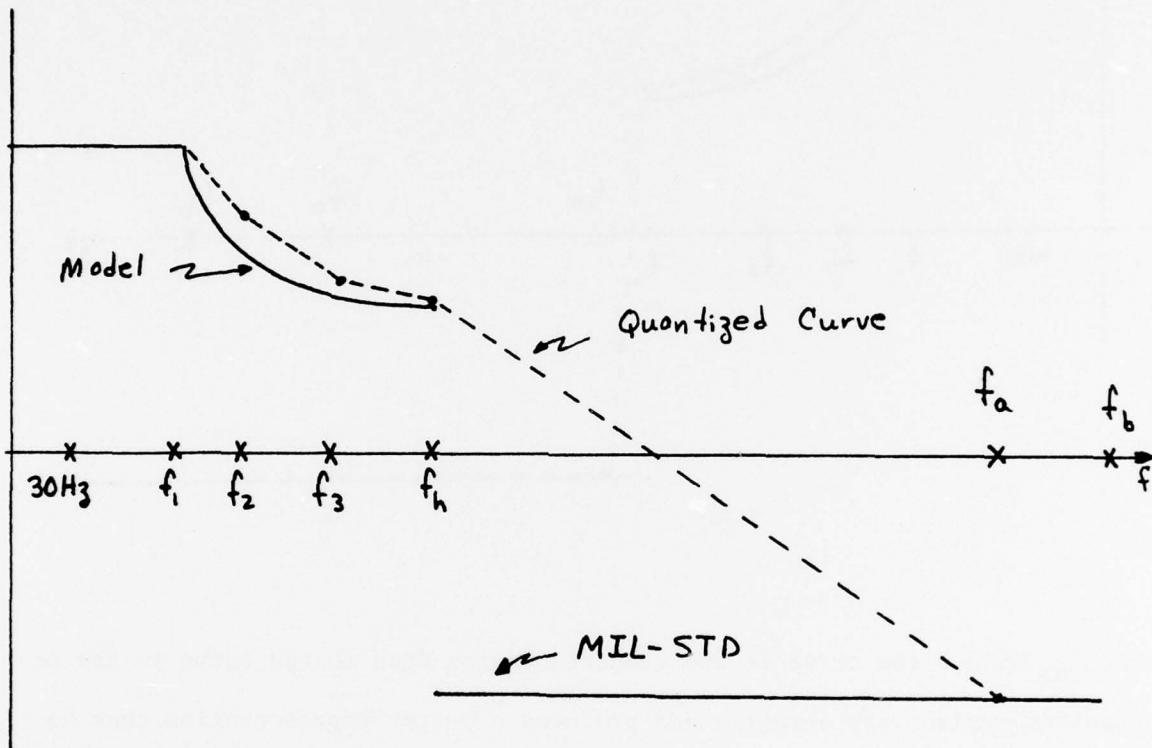
range for the Signal/Control Line Model). The parameter bwc defines this range so we choose $bwc = 20 f_m$. For all of these models (PDM, NRZPCM, BPPCM, PPM, RECTPL, PAM) the curves will have identical shapes; only the values of f_m will differ.

For the remaining Signal/Control Line Models and RF Models, the same technique was employed. However, for a few of the models,[†] the areas under the curves could not be obtained in terms of general parameters.[†]

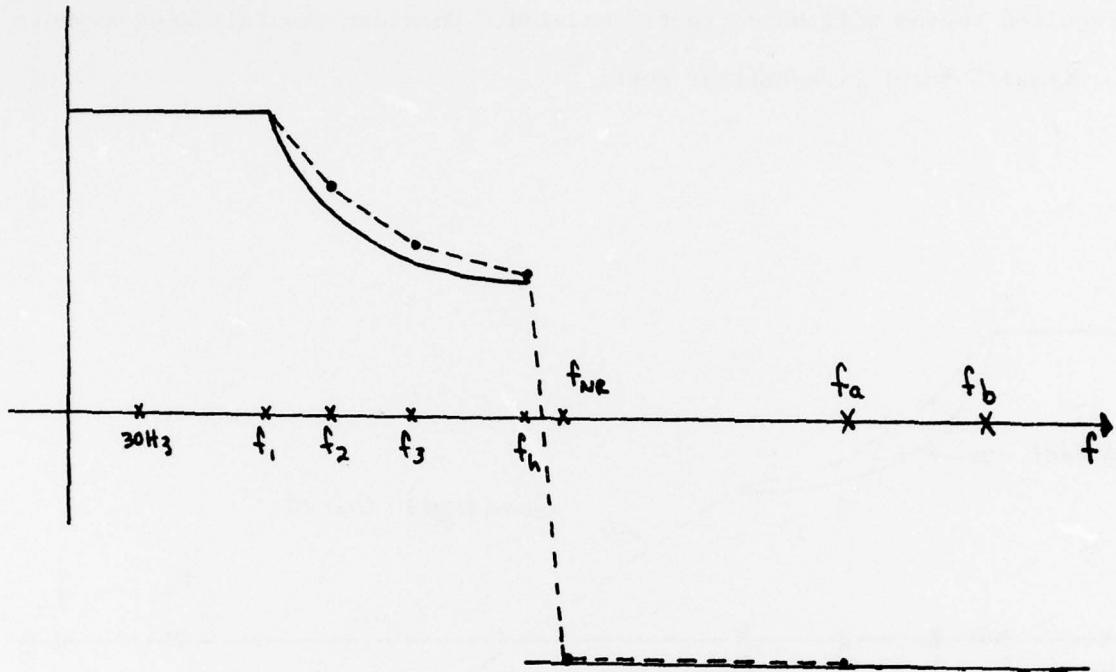
The frequencies which the program associates with each port of an equipment are input by the user in a frequency table (the FQTBL card). The values of the emitter and receptor spectra for all ports within this equipment at only those frequencies in the frequency table represent the port spectra. The actual values which are used, however, are the quantized values of the spectra. The quantized levels are the largest values for an emitter spectrum (smallest values for a receptor spectrum) within a range of halfway between the frequency and the next lower frequency and halfway between the frequency and the next higher frequency. To provide the user with guidelines for selecting the entries in the equipment frequency table such that the quantized spectra closely approximate the actual spectra, a list of frequencies for each type of emitter model follows each input parameter description. The entries on the equipment frequency table card (FQTBL) should contain the suggested frequencies for all ports in the equipment.

[†]For SAWTOOTH (S/C) and DAMPED SINUSOID (S/C), the criterion was to choose f_h such that the power spectral density curves are down by approximately 20 dB from their peak values. For BINARY FSK (RF), bwc was chosen such that the power spectral density curve is down by 20dB from its peak value.

Certain additional frequencies are required so that the transition between the model curve in the required region and the MIL-STD limit in the nonrequired region will be correctly modeled. Consider the following example of a Signal/Control line emitter port:



Five frequencies 30Hz , f_1 , f_2 , f_3 , f_h are selected for the required region. The next nearest frequencies (perhaps selected for some other port of the equipment which also contains this emitter), f_a and f_b , are in the nonrequired range for this emitter. The actual quantized curve used by the code is shown by a dashed line. Note that the representation of the MIL-STD limit from f_h to f_a is not very good. To fix this, we may add an additional frequency, f_{NR} , to the frequency table which is to the right of f_h and as close as possible to f_h . This results in:



and f_{NR} brings the curve in the required region down to the curve in the non-required region very abruptly and produces a better representation than before; the closer f_{NR} is to f_h , the better. We may choose this additional frequency to be

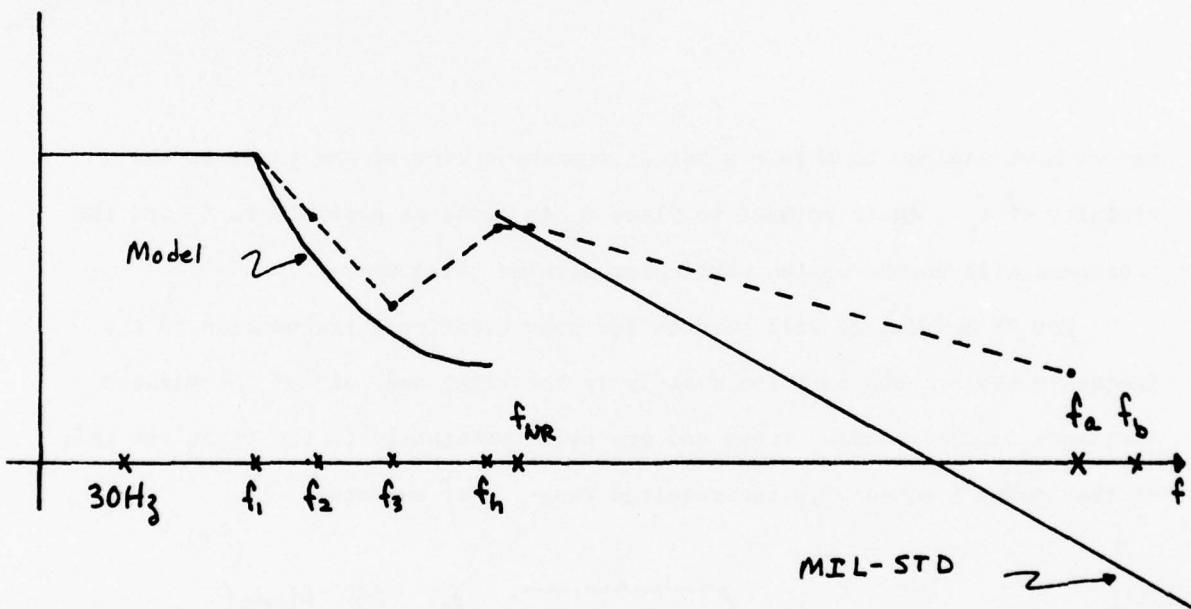
$$f_{NR} = f_h (1 + 10^{-P})$$

where P is a precision constant to be selected and P depends on the machine being used. For example, on an IBM 370/165 computer, we might choose

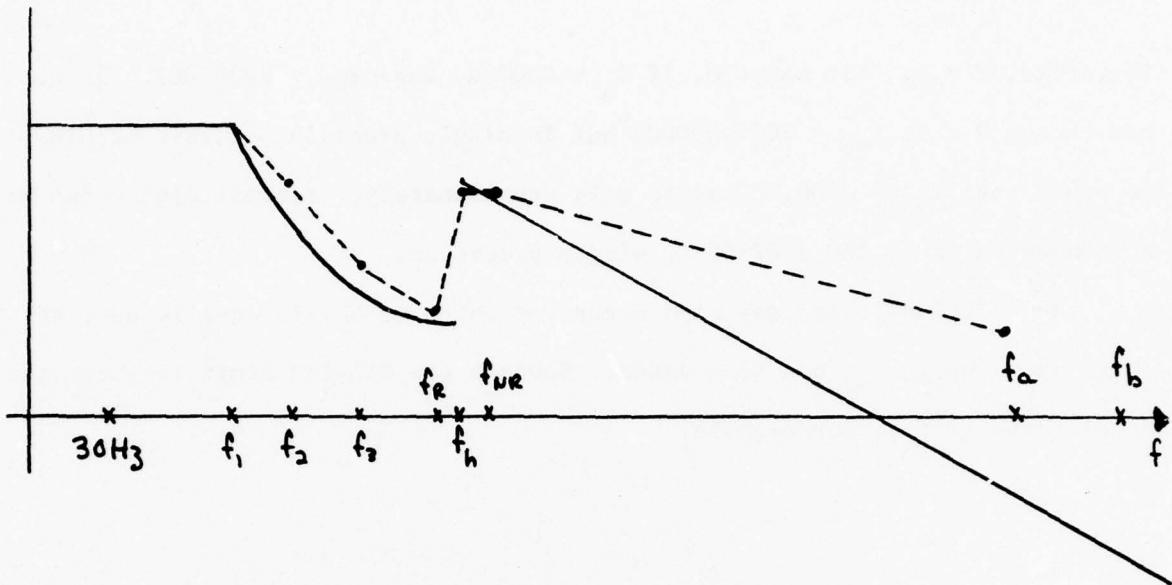
$$f_{NR} = (1.000001) f_h$$

Therefore, $P = 6$. For example, if $f_h = 2000\text{Hz}$, then $f_{NR} = 2000.002$. If we had chosen $P = 9$, $f_{NR} = 2000.000002$ but in single precision on this machine we would have $f_{NR} = 2000.000$ since only approximately 7 decimal digits can be accommodated on an IBM 370/165 in single precision.

An additional case may also occur for which we obtain equally poor results even though f_{NR} has been added. Suppose the MIL-STD limit is above the model curve at f_h . For example:

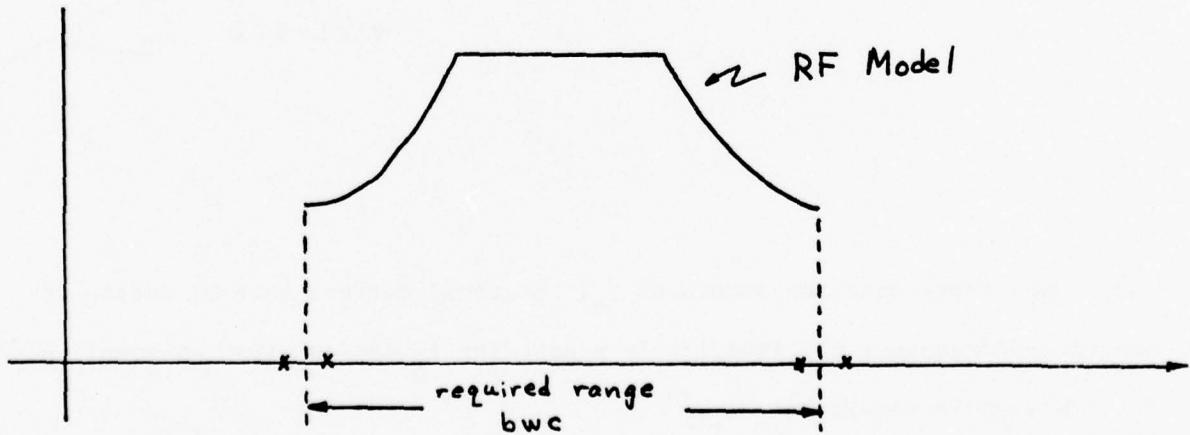


and a poor representation occurs at f_h . We could correct this by adding an additional frequency f_R , immediately preceding f_h and as close as possible to f_h . This would result in:



and we have managed to obtain a better representation of the curve in the vicinity of f_h . Again we want to place f_R as close as possible to f_h and the closeness will depend on the particular machine being used.

For RF models, we will need to add four additional frequencies to the frequency table: one pair immediately to the right and left of the highest frequency in the required range and one pair immediately to the right and left of the lowest frequency in the required range. For example:



These additional frequencies are included in the suggested list of frequencies to be included in the frequency table in terms of the particular machine precision constant P:

$$P < \left\{ \begin{array}{l} \text{the maximum number of decimal digits which can} \\ \text{be accommodated by the particular machine being} \\ \text{used} \end{array} \right\}$$

The frequencies suggested for inclusion in the frequency table must be listed in this table sequentially in terms of increasing value. For example, if three of the frequencies to be included in this table are 100Hz, 300Hz, and 4000Hz, these must be punched on the FQTBL card in the order

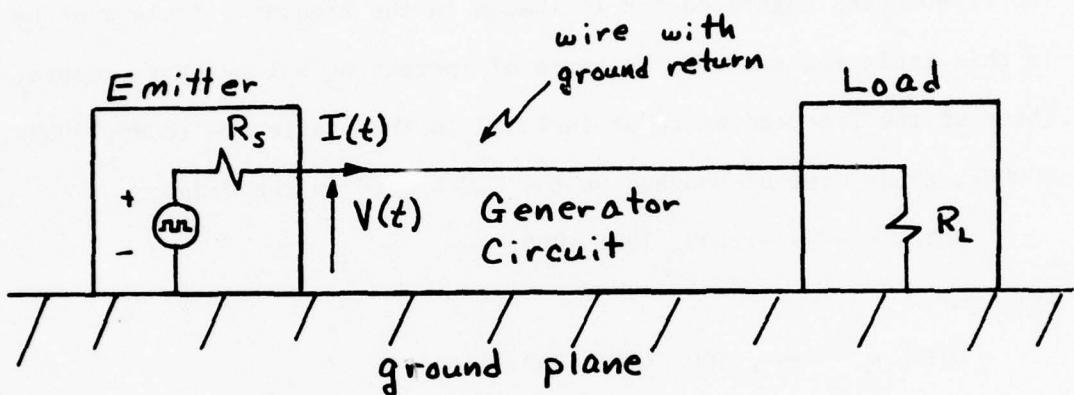
FQTBL = -----, 100, 300, 4000, ---

NOT

FQTBL = -----, 300, 100, 4000, ---

II. Signal/Control Line (S/C) Models:

The Signal/Control Line (S/C) Models are included to model the power spectral densities of emitters which transmit information over wires via cable bundles. For example, a typical emitter and its intended load are shown below.

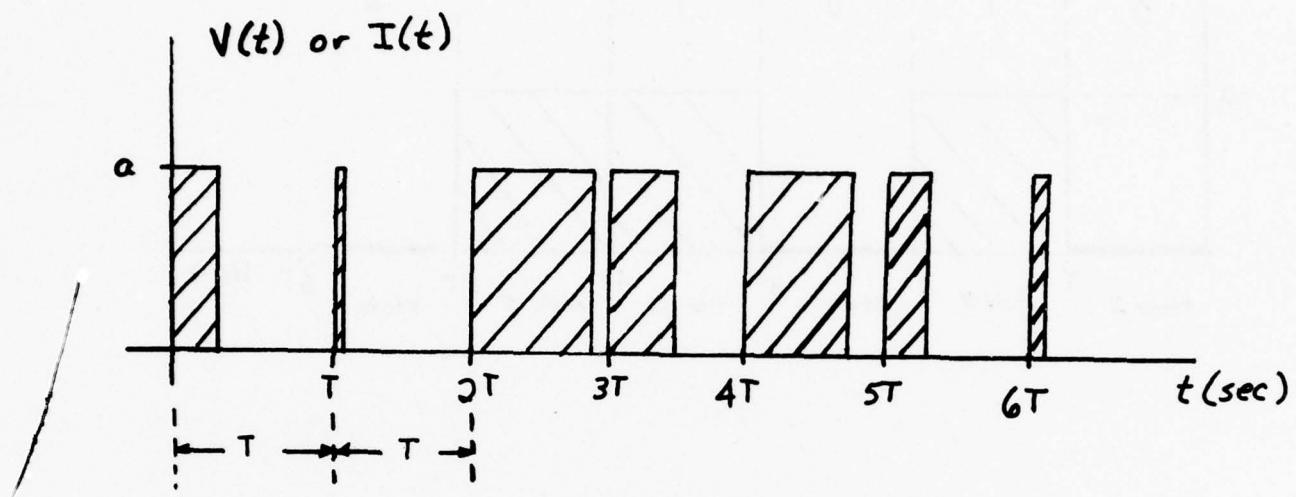


The wire-to-wire coupling portion of the program computes the induced voltage into a receptor circuit due to voltage $V(t)$ (or current $I(t)$). This coupling occurs when the wires comprising the receptor circuit are routed in the cable bundle containing the generator circuit wire.

The signal/control line waveforms discussed in this section are either $V(t)$ or $I(t)$ (the program handles either one and the user designates which units are intended in the input data by specifying VLTS or AMPS). This is an important distinction. The required parameters are associated with the waveform $V(t)$ or $I(t)$ produced at the output of the device when it is connected to its designated load.

Pulse Duration Modulation

(PDM)



Required Input Parameters:

a = volts/amps into designated load, R_L

r_b = bit rate $\left(r_b = \frac{1}{T} \right)$ (Hertz)

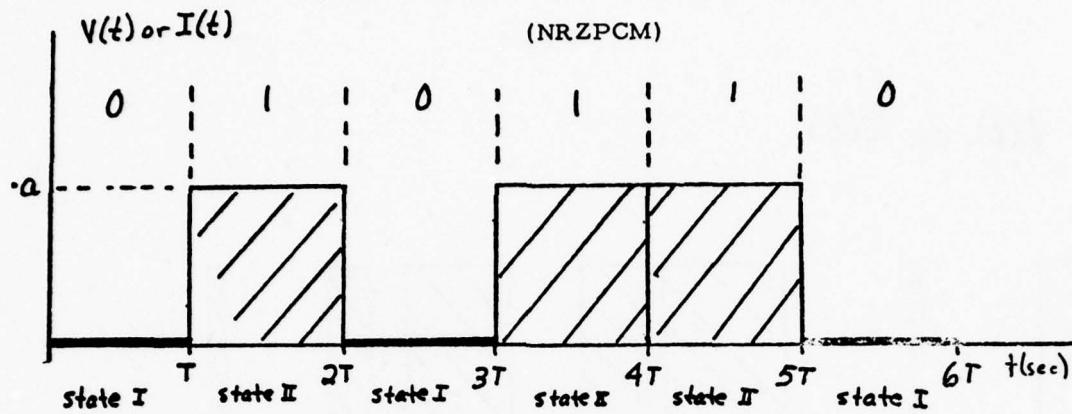
f_l = 30 Hz

f_h = 5.51 r_b Hz

Frequency Table (Hz):

$f_l, .1f_h, .2f_h, .35f_h, .55f_h, f_h, f_h (1 \pm 10^{-P})$

Pulse Code Modulation - Non Return to Zero



Required Input Parameters:

a = volts/amps into designated load, R_L

r_b = bit rate $\left(r_b = \frac{1}{T} \right)$ (Hertz)

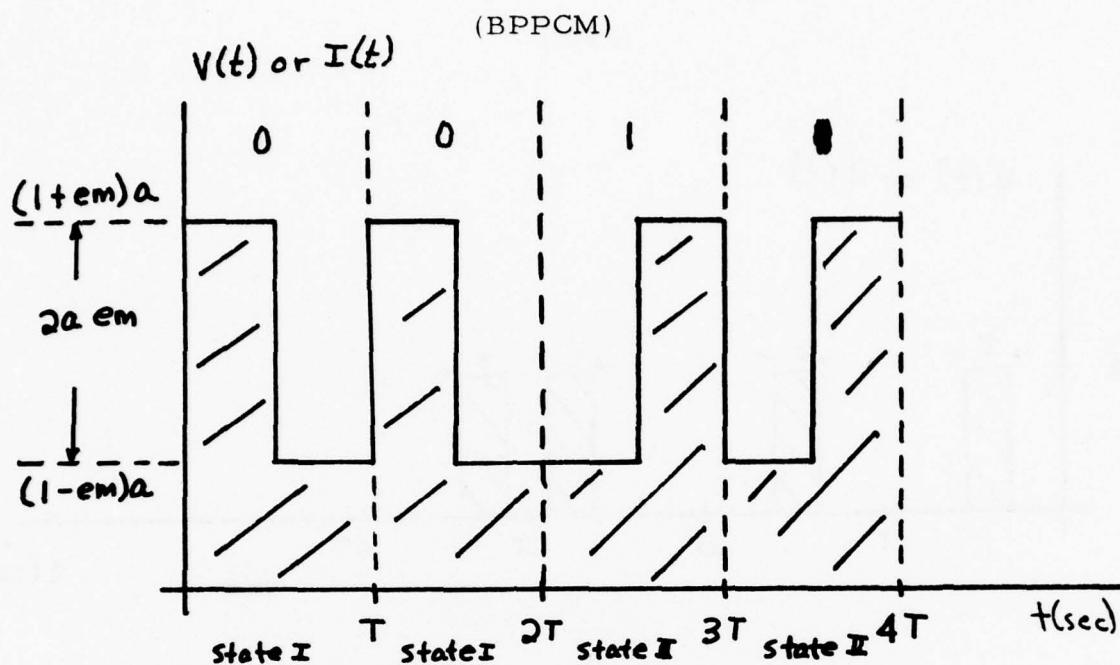
f_l = 30 Hz

$f_h = 3.18 r_b$ Hz

Frequency Table (Hz):

$f_l, .1f_h, .2f_h, .35f_h, .55f_h, f_h, f_h (1 \pm 10^{-P})$

Pulse Code Modulation - Biphasic



Required Input Parameters:

a = volts/amps into designated load, R_L

em = modulation index

r_b = bit rate ($r_b = \frac{1}{T}$) (Hertz)

f_l = 30 Hz

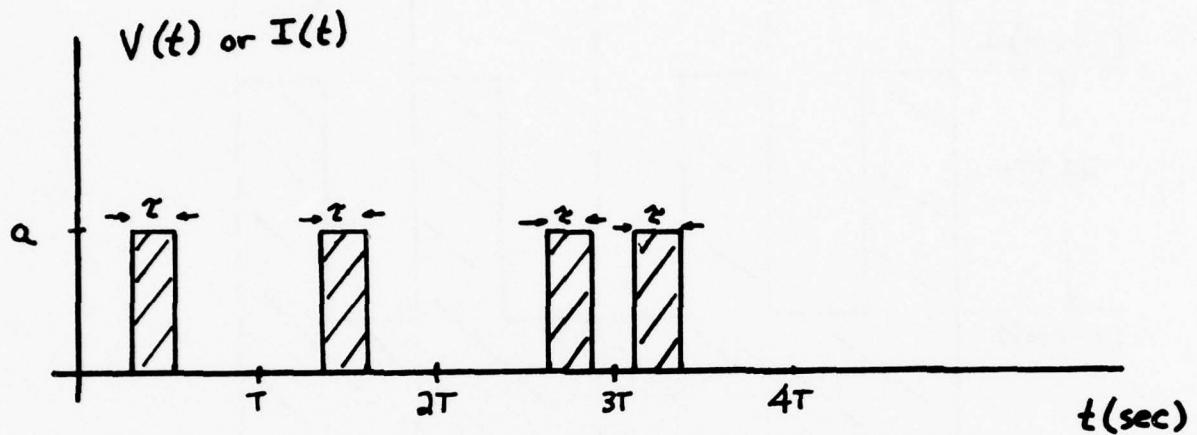
f_h = 10 r_b Hz

Frequency Table (Hz):

$f_l, .1f_h, .2f_h, .35f_h, .55f_h, f_h, f_h (1 \pm 10^{-P})$

Pulse Position Modulation

(PPM)



Required Input Parameters:

a = volts/amps into designated load, R_L

r_b = bit rate ($r_b = \frac{1}{T}$) (Hertz)

τ = pulse width (seconds)

f_L = 30 Hz

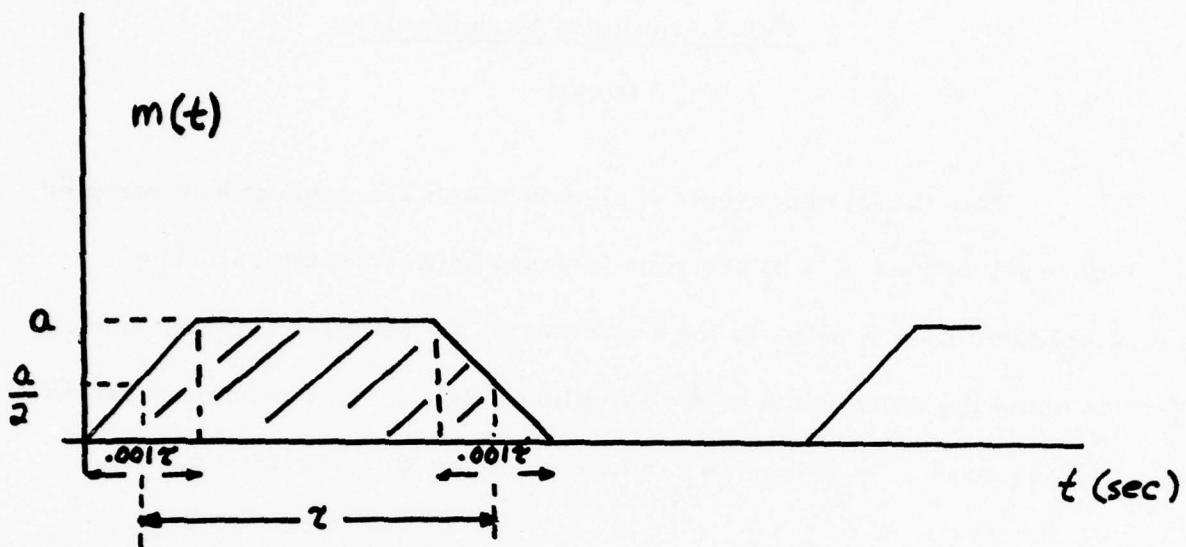
$f_h = 3.18/\tau$ Hz

Frequency Table (Hz):

$f_L, .1f_h, .2f_h, .35f_h, .55f_h, f_h, f_h (1 \pm 10^{-P})$

TELEGRAPHY

(TELEG)



$$V(t) \text{ or } I(t) = m(t) \cos(2\pi f_{\text{tone}} t)$$

$$\tau = \frac{.8}{\text{WPM}} \text{ (sec)} \quad \begin{aligned} \text{WPM} &= \text{Words Per Minute} \\ f_{\text{tone}} &= \text{tone modulation frequency} \end{aligned}$$

Required Input Parameters:

a = volts/amps into designated load, R_L

wpm = words per minute

f_{tone} = tone modulation frequency (Hertz)

f_ℓ = 30 Hz

$f_h = (3.98 \text{ wpm} + f_{\text{tone}}) \text{ Hz}$

Frequency Table (Hz):

$$\underline{f_{\text{tone}} = 0}$$

$f_\ell, .1f_h, .2f_h, .35f_h,$
 $.55f_h, f_h, f_h (1 \pm 10^{-P})$

$$\underline{f_{\text{tone}} \neq 0}$$

$f_\ell, f_{\text{tone}}, f_{\text{tone}} \pm .398 \text{ wpm},$
 $f_{\text{tone}} \pm .8 \text{ wpm}, f_{\text{tone}} \pm 1.4 \text{ wpm},$
 $f_{\text{tone}} \pm 2.2 \text{ wpm}, f_h, f_h (1 \pm 10^{-P})$

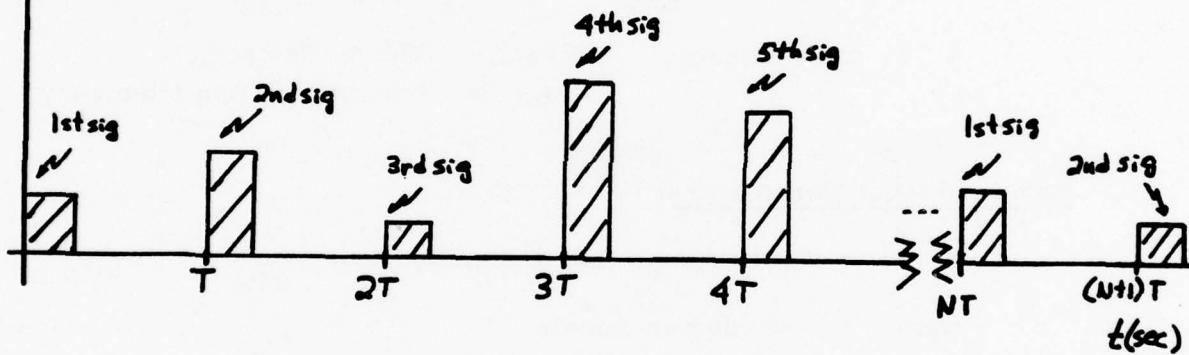
Note: Omit frequencies < 30Hz

Pulse Amplitude Modulation

(PAM)

This model represents N signals which are sequentially sampled every NT seconds. T is the time interval between samples. The amplitude of each pulse is the amplitude of the sampled signal at that time and the pulse width of the sampling pulse is τ . The sample values are assumed to be Gaussian random variables with variance σ^2 .

$V(t)$ or $I(t)$



Required Input Parameters:

$$a = \left(\frac{N\sigma^2}{2} \right)^{1/2} \quad (\text{Volts/Amps})$$

τ = width of sampling pulse (seconds)

$$r_b = \text{bit rate} \quad (r_b = \frac{1}{T}) \quad (\text{Hertz})$$

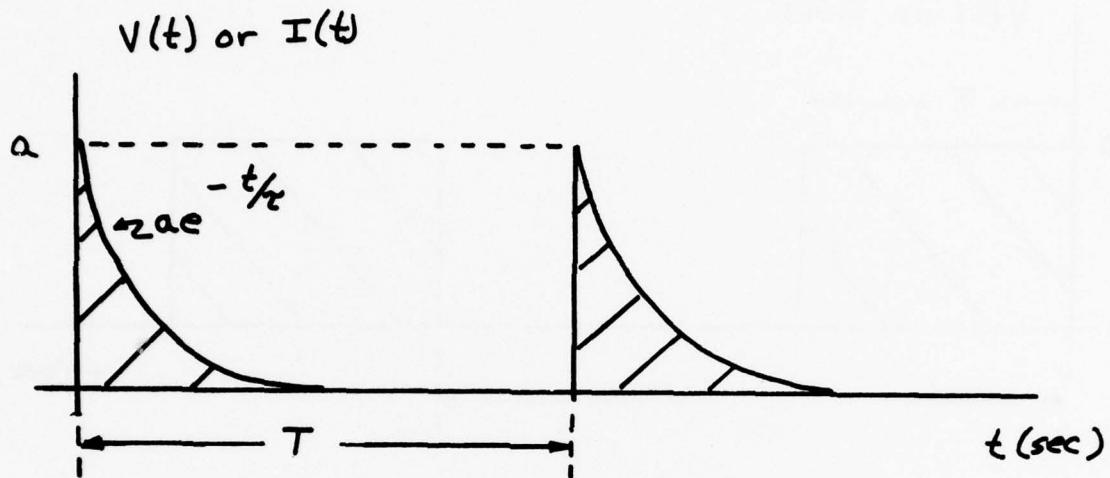
$$f_l = 30 \text{ Hz}$$

$$f_h = 3.18/\tau \text{ Hz}$$

Frequency Table (Hz):

$$f_l, .1f_h, .2f_h, .35f_h, .55f_h, f_h, f_h (1 \pm 10^{-P})$$

Exponential Decay Spike Pulse Train
(ESPIKE)



Required Input Parameters:

a = volts/amps into designated load, R_L

τ = decay time constant (time required to decay to A/e) (seconds)

r_b = bit rate ($r_b = \frac{1}{T}$) (Hertz)

f_l = 30 Hz

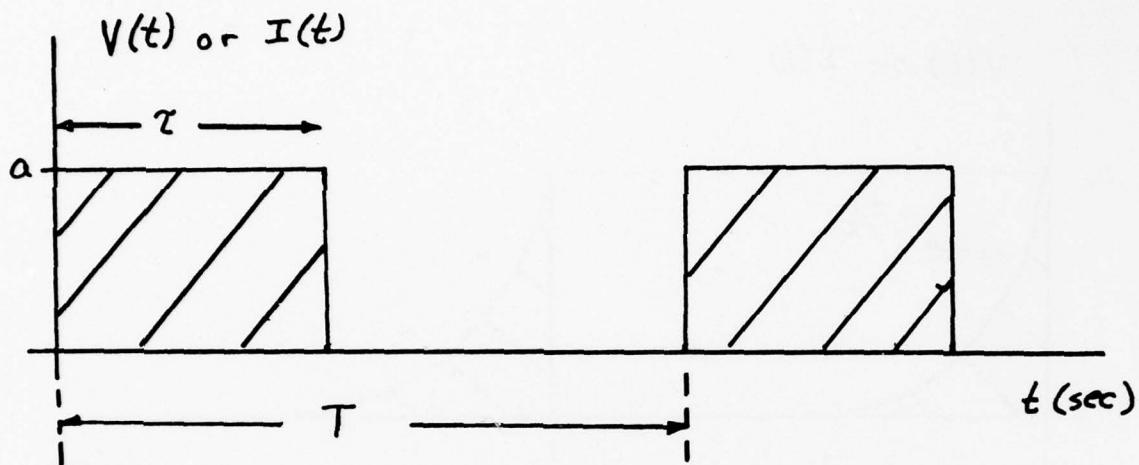
f_h = $2/\tau$ Hz

Frequency Table (Hz):

$f_l, .08f_h, .16f_h, .26f_h, .38f_h, .54f_h, .9f_h, f_h, f_h (1 \pm 10^{-P})$

Rectangular Pulse Train

(RECTPL)



Required Input Parameters:

a = volts/amps into designated load, R_L

τ = pulse width (seconds)

r_b = bit rate ($r_b \approx \frac{1}{T}$) (Hertz)

f_l = 30 Hz

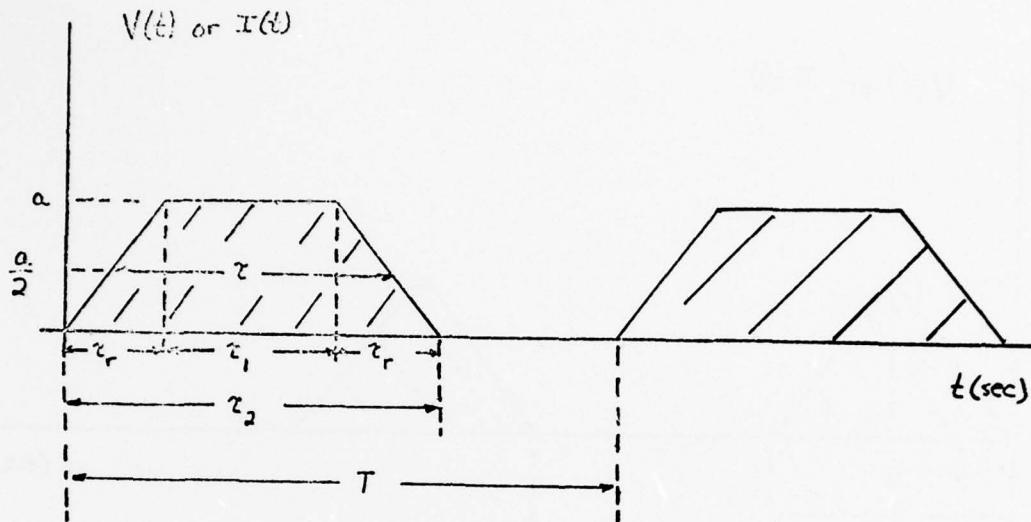
$f_h = 3.18/\tau$ Hz

Frequency Table (Hz):

$f_l, .1f_h, .2f_h, .35f_h, .55f_h, f_h, f_h(1 \pm 10^{-P})$

Trapezoidal Pulse Train

(TPZD)



Required Input Parameters:

a = volts/amps into designated load, R_L

r_b = bit rate ($r_b = \frac{1}{T}$) (Hertz)

τ = pulse width ($\tau = \frac{\tau_1 + \tau_2}{2}$) (seconds)

τ_r = pulse rise/fall time ($\tau_r = \frac{\tau_2 - \tau_1}{2}$) (seconds)

$$\tau = \alpha \tau_r$$

$$\alpha \leq 3.67$$

$$f_l = 30 \text{ Hz}$$

$$f_h = \left(\frac{1}{.3\alpha - .1} \right)^{1/3} \frac{\alpha}{\pi \tau}$$

$$\alpha \geq 3.67$$

$$f_l = 30 \text{ Hz}$$

$$f_h = \left(\frac{3\alpha}{.3\alpha + 1.9} \right) \frac{1}{\pi \tau}$$

Frequency Table (Hz): ($f_{m1} = 1/\pi\tau$, $f_{m2} = \alpha f_{m1}$)

$$\underline{\alpha \leq 3.67}$$

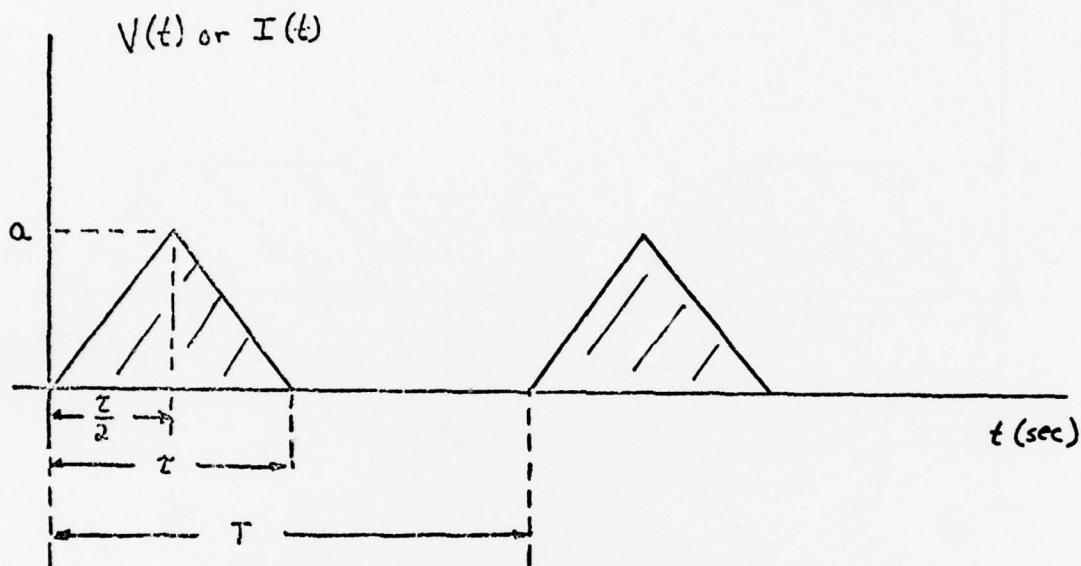
$$f_l, f_{m1}, \frac{(f_{m1} + f_{m2})}{2}, f_{m2}, \frac{(f_h + f_{m2})}{2}, f_h, \\ f_h (1 \pm 10^{-p})$$

$$\overline{\alpha > 3.67}$$

$$f_l, f_{m1}, \frac{(f_{m1} + f_h)}{2}, f_h, f_h (1 \pm 10^{-p})$$

Triangular Pulse Train

(TRIANG)



Required Input Parameters:

a = volts/amps into designated load, R_L

r_b = bit rate ($r_b = \frac{1}{T}$) (Hertz)

τ = pulse duration (seconds)

f_l = 30 Hz

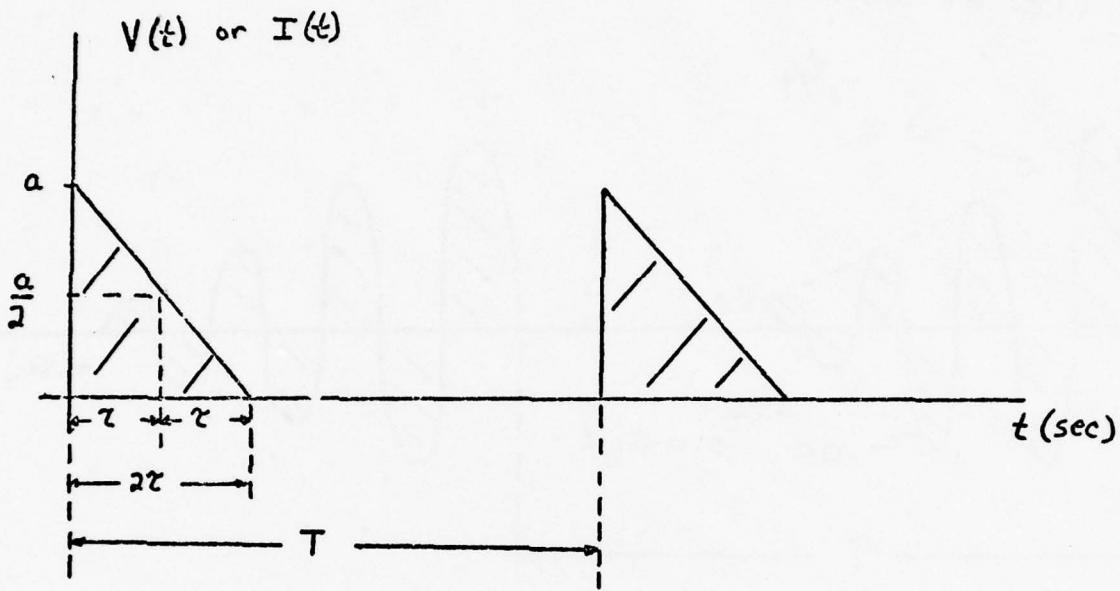
f_h = $1.08/\tau$ Hz

Frequency Table (Hz):

$f_l, .59f_h, .82f_h, f_h, f_h(1 \pm 10^{-P})$

Sawtooth Pulse Train

(SA WTH)



Required Input Parameters:

a = volts/amps into designated load, R_L

r_b = bit rate ($r_b = \frac{1}{T}$) (Hertz)

τ = pulse width (to decay to $\frac{a}{2}$) (seconds)

f_l = 30 Hz

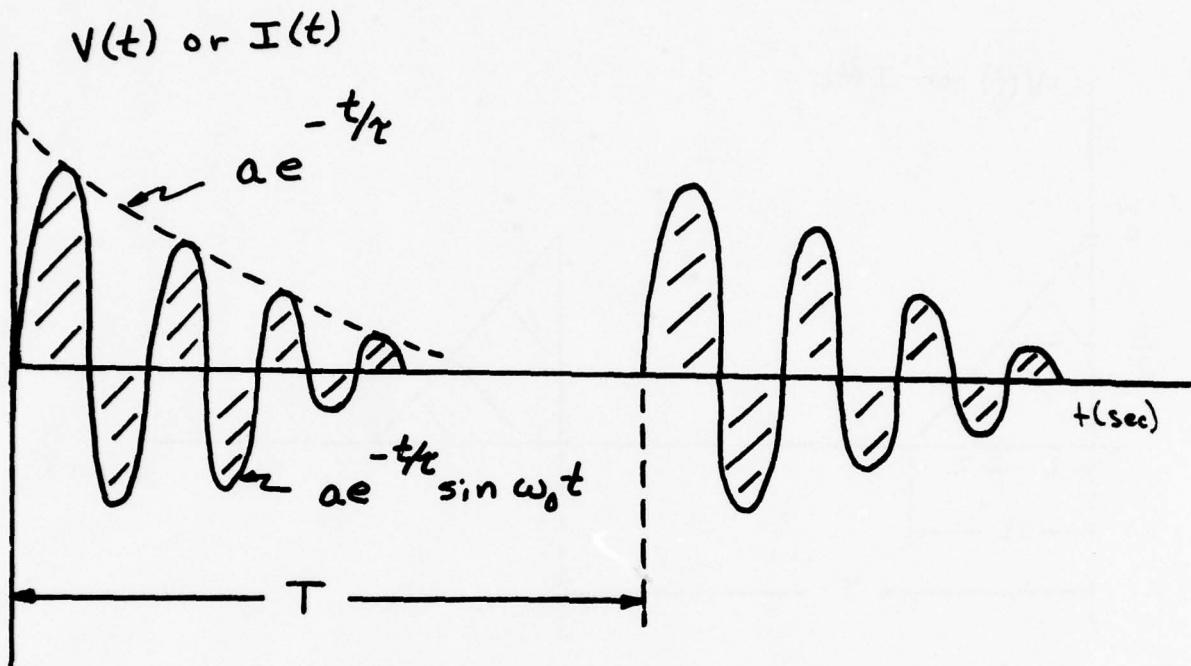
f_h = $1.52/\tau$ Hz

Frequency Table (Hz):

$f_l, .13f_h, .18f_h, .26f_h, .34f_h, .39f_h, .61f_h, .76f_h, f_h, f_h (1 \pm 10^{-P})$

Damped Sinusoid Pulse Train

(DMPSIN)



Required Input Parameters:

a = volts/amps into designated load, R_L

r_b = bit rate ($r_b = \frac{1}{T}$) (Hertz)

f_r = frequency of sinusoid ($\omega_0 = 2\pi f_r$) (Hertz)

f_I = inverse of decay constant ($f_I = \frac{1}{\tau}$) (1/seconds)

f_ℓ = 30 Hz

$f_h = (f_r + 12.7f_I)$ Hz

Frequency Table (Hz):

$f_r, f_r \pm .8f_I, f_r \pm 2f_I, f_r \pm 4.4f_I, f_r \pm 7.6f_I, f_r \pm 12.7f_I,$

Note: Omit frequencies < 30 Hz. $(f_r + 12.7f_I)(1 \pm 10^{-P})$,

$(f_r - 12.7f_I)(1 \pm 10^{-P})$

Voice

(VOICE)

No input parameters. The model is based on a statistical average of representative voice signals.

$$f_l = 30 \text{ Hz}$$

$$f_h = 4400 \text{ Hz}$$

Frequency Table (Hz):

30, 45, 70, 100, 200, 1000, 4000, 4400(1 ± 10^{-P})

Clipped Voice

(CVOICE)

No input parameters. The model is based on a statistical average of representative clipped voice signals.

$$f_l = 30 \text{ Hz}$$

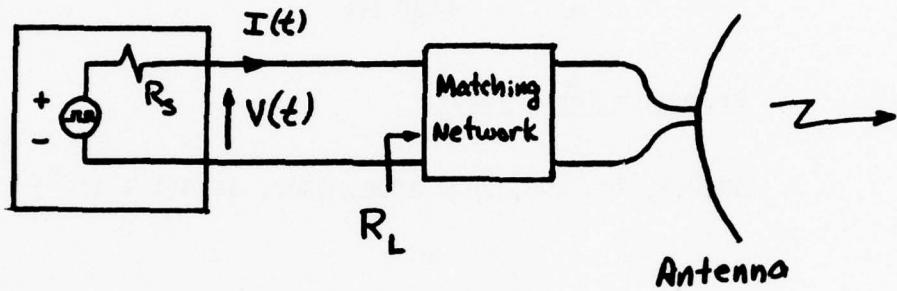
$$f_h = 3200 \text{ Hz}$$

Frequency Table (Hz):

30, 50, 100, 350, 750, 1000, 3200, 3200 (1 ± 10^{-P})

III. RF Emitter Models:

These types of emitter models are intended to characterize radio frequency transmitters which are connected to antennas.



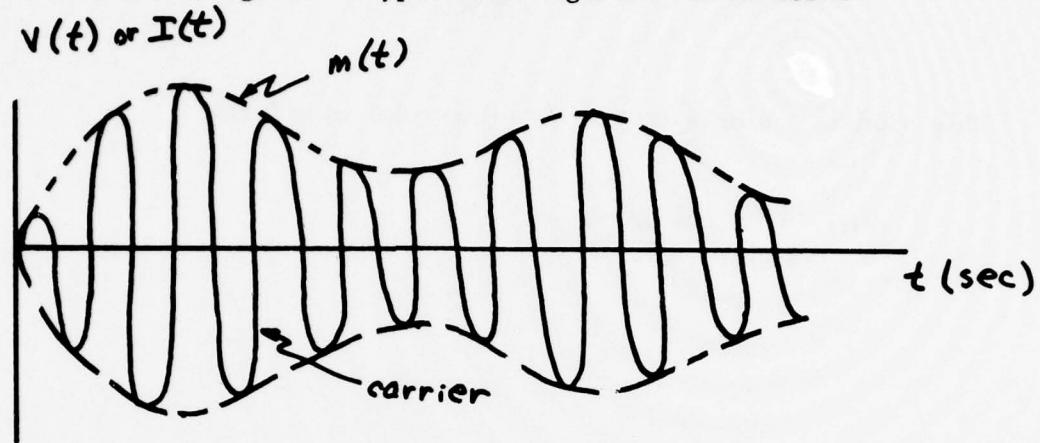
The power into the designated load, R_L , is required as one important input parameter. If the matching network is lossless then this quantity is directly related to the power radiated by the antenna.

The format for the RF Emitter Models will be quite similar to the format for the Signal/Control Line Emitter Models with one important distinction. In all of these cases a carrier frequency, f_c , is modulated by the information by either amplitude modulation of the carrier (AM) or frequency modulation of the carrier (FM).

In amplitude modulation, we will designate the voltage, $V(t)$, (or current, $I(t)$,) as

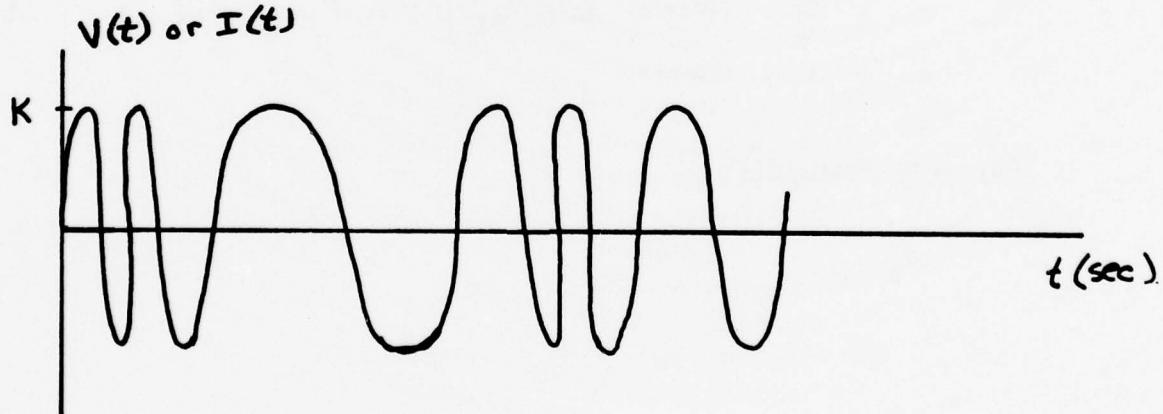
$$V(t) = m(t) \cos (2\pi f_c t + \phi)$$

where f_c is the carrier frequency, ϕ is a phase angle and $m(t)$ is the time-domain modulation signal. A typical AM signal is shown below.



Only the waveform of $m(t)$ will be shown.

In frequency modulation, the modulating signal varies the carrier frequency. A typical FM signal is shown below.



Again only the modulation signal, $m(t)$, will be shown and the general form of an FM signal is

$$V(t) = K \cos \left[2\pi f_c t + 2\pi \Delta \int_0^t m(\tau) d\tau \right]$$

where Δ is the frequency deviation constant and f_c is the carrier frequency.

Continuous Wave

(CW)

This models a single frequency sinusoidal waveform:

$$V(t) = a \cos (2\pi f_c t)$$

Required Input Parameters:

$$f_l = f_h = f_c \text{ (Hertz)}$$

$$P = \frac{a^2}{2} \text{ (Watts)} \quad \left\{ \begin{array}{l} \text{Multiply by } 1/R_L \text{ if } V(t) \text{ is a voltage} \\ \text{and } R_L \text{ if } V(t) \text{ is a current} \end{array} \right\}$$

$$bwc = 1 \text{ (Hertz)}$$

Frequency Table (Hz):

$$f_c$$

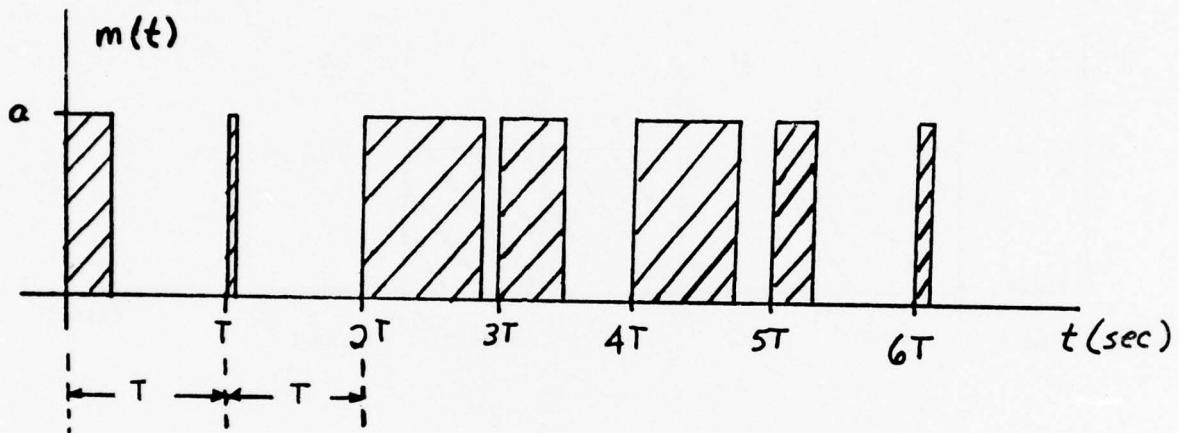
Pulse Duration Modulation/AM

(PDM)

Waveform is:

$$V(t) = m(t) \cos (2\pi f_c t + \phi)$$

$m(t)$ is PDM S/C modulation:



Required Input Parameters:

$f_l = f_h = \text{carrier frequency } f_c \text{ (Hertz)}$

$P = \frac{a^2}{2} \text{ (Watts)} \quad \left\{ \begin{array}{l} \text{Multiply by } 1/R_L \text{ if } V(t) \text{ is a voltage} \\ \text{and } R_L \text{ if } V(t) \text{ is a current} \end{array} \right\}$

$r_b = \text{bit rate of modulation } \left(r_b = \frac{1}{T} \right) \text{ (Hertz)}$

$bwc = 11.03 r_b \text{ (Hertz)}$

Frequency Table (Hz):

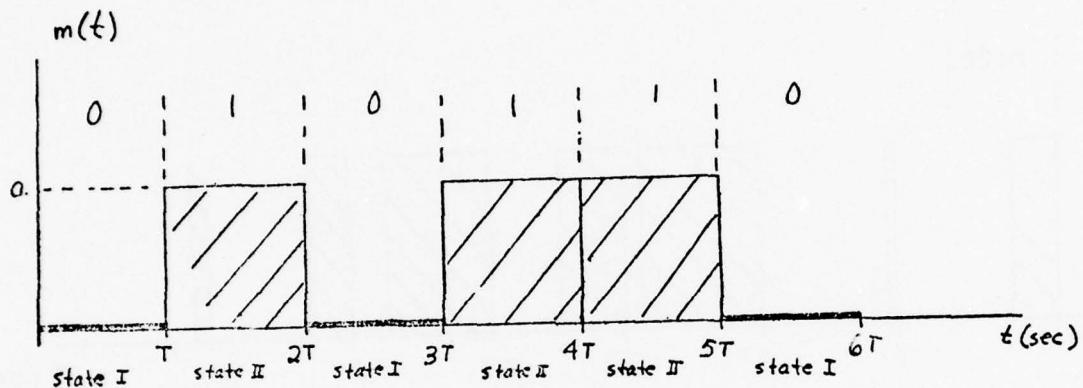
$f_c, f_c \pm .05bwc, f_c \pm .1bwc, f_c \pm .175bwc, f_c \pm .275 bwc, f_c \pm .5bwc,$
 $(f_c + .5 bwc) (1 \pm 10^{-P}), (f_c - .5 bwc) (1 \pm 10^{-P})$

Pulse Code Modulation - Non Return to Zero/AM
 (NRZPCM)

Waveform is:

$$V(t) = m(t) \cos(2\pi f_c t + \phi)$$

$m(t)$ is PCM-NRZ S/C modulation:



Required Input Parameters:

$f_c = f_h = \text{carrier frequency } f_c \text{ (Hertz)}$

$p = \frac{a^2}{2} \text{ (Watts)} \quad \left\{ \begin{array}{l} \text{Multiply by } 1/R_L \text{ if } V(t) \text{ is a voltage} \\ \text{and } R_L \text{ if } V(t) \text{ is a current} \end{array} \right\}$

$r_b = \text{bit rate of modulation } \left(r_b = \frac{1}{T} \right) \text{ (Hertz)}$

$$bwc = 6.37 r_b \text{ (Hertz)}$$

Frequency Table (Hz):

$f_c, f_c \pm .05bwc, f_c \pm .1bwc, f_c \pm .175bwc, f_c \pm .275bwc, f_c \pm .5bwc,$

$$(f_c + .5 bwc) (1 \pm 10^{-P}), (f_c - .5 bwc) (1 \pm 10^{-P})$$

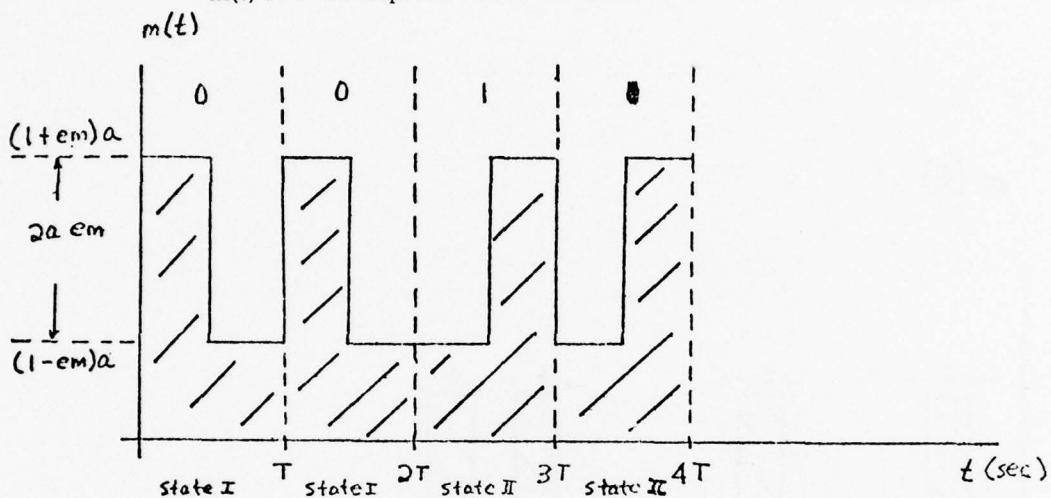
Pulse Code Modulation - Biphasic/AM

(BPPCM)

Waveform is:

$$V(t) = m(t) \cos(2\pi f_c t + \phi)$$

$m(t)$ is PCM-Biphase S/C modulation:



Required Input Parameters:

$f_c = f_h = \text{carrier frequency } f_c \text{ (Hertz)}$

$p = \frac{a^2}{2} \text{ (Watts)} \quad \left\{ \begin{array}{l} \text{Multiply by } 1/R_L \text{ if } V(t) \text{ is a voltage} \\ \text{and } R_L \text{ if } V(t) \text{ is a current} \end{array} \right\}$

$r_b = \text{bit rate of modulation } \left(r_b = \frac{1}{T} \right) \text{ (Hertz)}$

$\text{em} = \text{modulation index}$

$bwc = 20 r_b \text{ (Hertz)}$

Frequency Table (Hz):

$f_c, f_c \pm .05bwc, f_c \pm .1bwc, f_c \pm .175bwc, f_c \pm .275bwc, f_c \pm .5bwc,$
 $(f_c + .5 bwc) (1 \pm 10^{-P}), (f_c - .5 bwc) (1 \pm 10^{-P})$

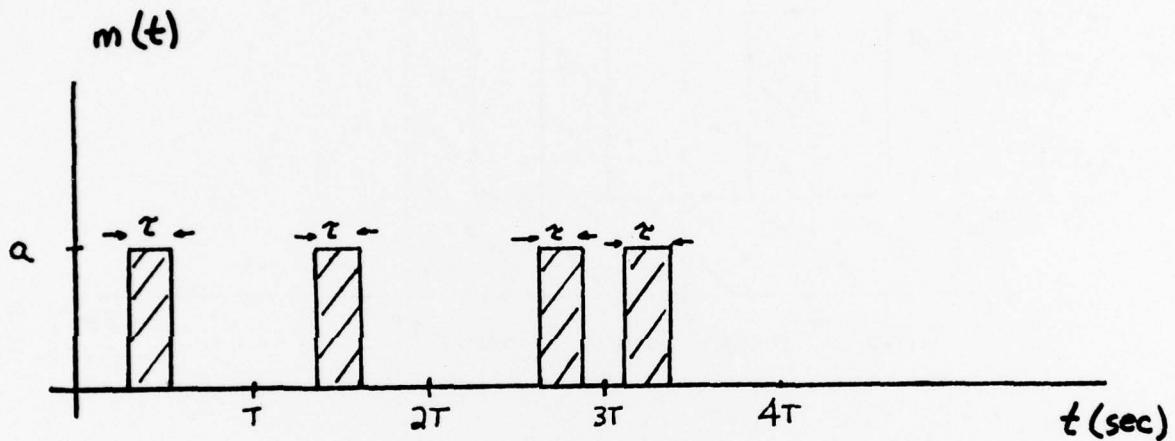
Pulse Position Modulation/AM

(PPM)

Waveform is:

$$V(t) = m(t) \cos (2\pi f_c t + \phi)$$

$m(t)$ is PDM S/C modulation:



Required Input Parameters:

$f_l = f_h = \text{carrier frequency } f_c \text{ (Hertz)}$

$p = a^2 \text{ (Watts)} \quad \left\{ \begin{array}{l} \text{Multiply by } 1/R_L \text{ if } V(t) \text{ is a voltage} \\ \text{and } R_L \text{ if } V(t) \text{ is a current} \end{array} \right\}$

$r_b = \text{bit rate of modulation } \left(r_b = \frac{1}{T} \right) \text{ (Hertz)}$

$\tau = \text{pulse width (seconds)}$

$$\text{bwc} = 6.37/\tau \text{ (Hertz)}$$

Frequency Table (Hz):

$f_c, f_c \pm .05\text{bwc}, f_c \pm .1\text{bwc}, f_c \pm .175\text{ bwc}, f_c \pm .275\text{ bwc}, f_c \pm .5\text{ bwc},$
 $(f_c + .5\text{ bwc}) (1 \pm 10^{-P}), (f_c - .5\text{ bwc}) (1 \pm 10^{-P})$

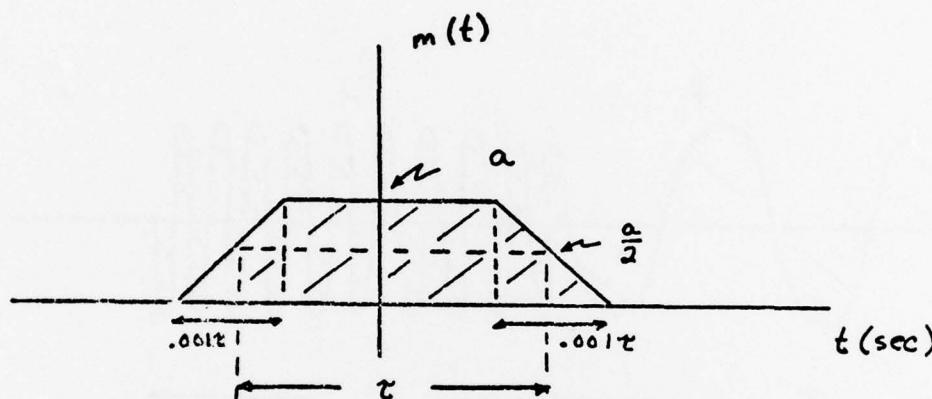
Telegraphy/AM

(TELEG)

Waveform is:

$$V(t) = m(t) \cos(2\pi f_{tone} t) \cos(2\pi f_c t)$$

where $m(t)$ is a sequence of trapezoidal pulses:



$$\tau = \frac{.8}{WPM} \text{ (sec)} \quad WPM = \text{Words Per Minute}$$

$$f_{tone} = \text{tone modulation frequency}$$

Required Input Parameters:

$f_l = f_h = \text{carrier frequency } f_c \text{ (Hertz)}$

$P = \frac{a^2}{2} \text{ (Watts)}$ {Multiply by $1/R_L$ if $V(t)$ is a voltage
and R_L if $V(t)$ is a current}

wpm = Words Per Minute

$f_{tone} = f_{tone}$ (Hertz)

bwc = $7.96wpm + 2f_{tone}$

Frequency Table (Hz):

$f_{tone} = 0$

$f_c, f_c \pm .398wpm, f_c \pm .8wpm, f_c \pm 1.4wpm,$

$f_c \pm 2.2wpm, f_c \pm 3.98wpm$

$(f_c + 3.98 \text{ wpm}) (1 \pm 10^{-P}),$

$(f_c - 3.98 \text{ wpm}) (1 \pm 10^{-P})$

$f_{tone} \neq 0$

$f_c, f_c \pm (.398wpm + f_{tone}), f_c \pm$

$(.8wpm + f_{tone}), f_c \pm (1.4wpm +$

$f_{tone}), f_c \pm (2.2wpm + f_{tone}), f_c \pm$

$(3.98wpm + f_{tone}), (f_c + 3.98 \text{ wpm} +$

$f_{tone}) (1 \pm 10^{-P}), (f_c - 3.98 \text{ wpm} -$

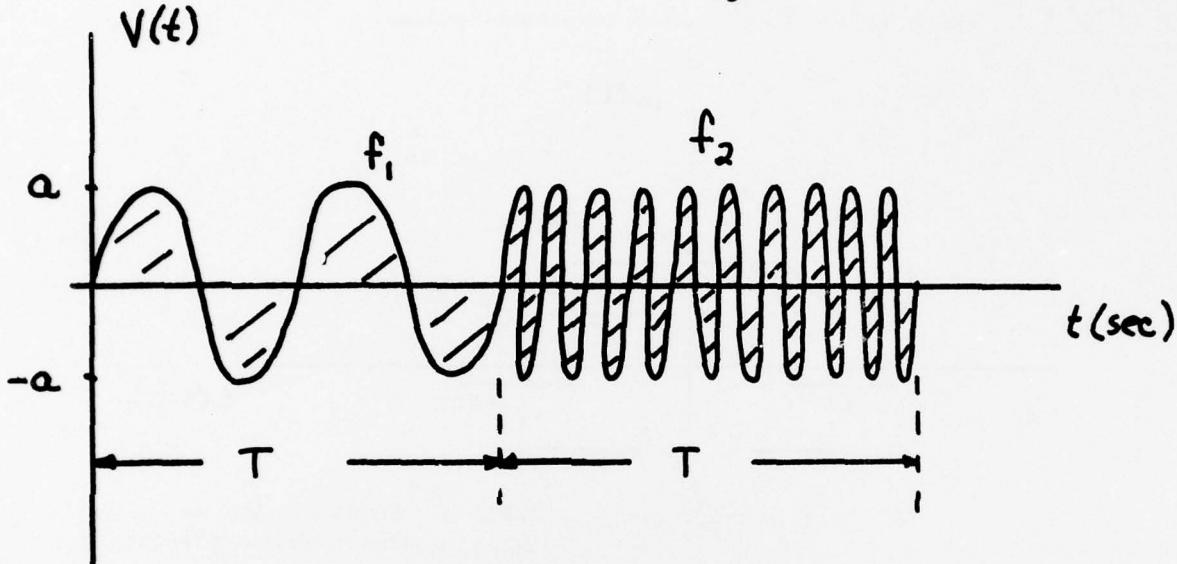
$f_{tone}) (1 \pm 10^{-P})$

Binary Frequency Shift Keying /FM

(FSK)

Waveform is:

$$V(t) = a \cos [2\pi f_c t + \Delta\omega \int_{t_0}^t m(t') dt' + \phi]$$



where $m(t)$ is a binary waveform which can assume the values of +1 or -1 with probability 0.5. Transitions in frequency (between $f_c \pm \frac{\Delta\omega}{2\pi}$) are separated by the bit interval T .

Required Input Parameters:

$$f_c = f_h = \text{carrier frequency} = \frac{f_1 + f_2}{2} \text{ (Hertz)}$$

$$P = \frac{a^2}{2} \text{ (Watts)} \quad \left\{ \begin{array}{l} \text{Multiply by } 1/R_L \text{ if } V(t) \text{ is a voltage} \\ \text{and } R_L \text{ if } V(t) \text{ is a current} \end{array} \right\}$$

$$r_b = \text{bit rate } \left(\frac{1}{T} \right) \text{ (seconds)}$$

$$\text{diff} = |f_1 - f_2| \text{ (Hertz)}$$

(continued)

(PSK)

$$\text{diff} \geq -\frac{4}{\pi^2} r_b :$$

$$bwc = \sqrt{\text{diff}(\text{diff} + \frac{40r_b}{\pi^2})}$$

$$\text{diff} < -\frac{4}{\pi^2} r_b :$$

$$bwc = \sqrt{\text{diff} \left\{ \text{diff} + \frac{20r_b(2\text{diff})}{\pi^2 r_b} \right\}^{1/3}}$$

Frequency Table (Hz):

$$f_c, f_c \pm [\alpha + .25\beta], f_c \pm [\alpha + .5\beta],$$

$$f_c \pm [\alpha + .75\beta], f_c \pm [\alpha + \beta],$$

$$(f_c + \alpha + \beta) (1 \pm 10^{-P}), (f_c - \alpha - \beta) (1 \pm 10^{-P})$$

$$f_c = \frac{f_1 + f_2}{2}$$

$$\text{diff} \geq -\frac{4}{\pi^2} r_b :$$

$$\alpha = \frac{\text{diff}}{2} \sqrt{1 + \frac{4r_b}{\pi^2 \text{diff}}}$$

$$\beta = \frac{bwc}{2} - \alpha$$

$$\text{diff} < -\frac{4}{\pi^2} r_b :$$

$$\alpha = \frac{\text{diff}}{2} \sqrt{1 + \frac{2r_b}{\pi \text{diff}} \left(\sqrt[3]{\frac{2\text{diff}}{\pi r_b}} \right)}$$

$$\beta = \frac{bwc}{2} - \alpha$$

Pulse Amplitude Modulation/FM

(PAMFM)

The PAMFM signal is a carrier which is frequency modulated by the PAM S/C modulation. a is the amplitude of the FM carrier, N signals are sampled, f_m is the maximum frequency of the information in each sample, σ is the variance of each sample, and τ is the sampling pulse width.

Required Input Parameters:

$$p = a^2 N f_m \tau \quad (\text{Watts}) \quad \left\{ \begin{array}{l} \text{Multiply by } 1/R_L \text{ if } V(t) \text{ is a voltage} \\ \text{and } R_L \text{ if } V(t) \text{ is a current} \end{array} \right\}$$

$$df = 3\sigma$$

$$bwc = 4\sigma \quad (\text{Hertz})$$

Frequency Table (Hz):

$$f_c, f_c \pm \sigma, f_c \pm 2\sigma, (f_c + 2\sigma) (1 \pm 10^{-P}), (f_c - 2\sigma) (1 \pm 10^{-P})$$

RADAR

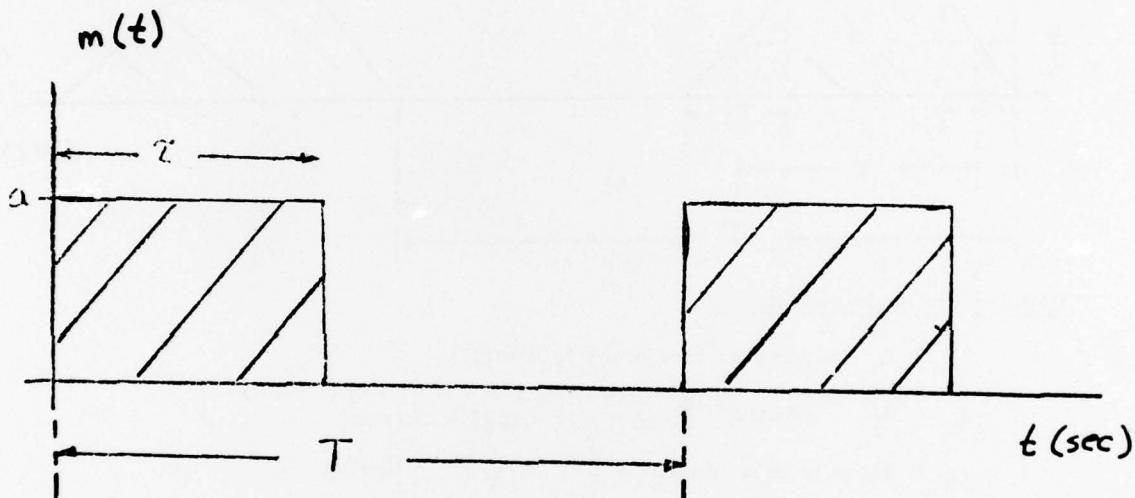
Rectangular Pulse

(RADAR, RECTPL)

Waveform is:

$$V(t) = m(t) \cos(2\pi f_c t + \phi)$$

$m(t)$ is Rectangular Pulse Train S/C modulation:



Required Input Parameters:

$f_c = f_h = \text{carrier frequency } f_c \text{ (Hertz)}$

$P = \frac{a^2}{2} \text{ (Watts)} \quad \left\{ \begin{array}{l} \text{Multiply by } 1/R_L \text{ if } V(t) \text{ is a voltage} \\ \text{and } R_L \text{ if } V(t) \text{ is a current} \end{array} \right\}$

$r_b = \text{bit rate of modulation } \left(r_b = \frac{1}{T} \right) \text{ (Hertz)}$

$\tau = \text{pulse width (seconds)}$

$$bwc = 6.37/\tau \text{ (Hertz)}$$

Frequency Table (Hz):

$f_c, f_c \pm .05bwc, f_c \pm .1bwc, f_c \pm .175bwc, f_c \pm .275bwc, f_c \pm .5bwc,$

$$(f_c + .5 bwc) (1 \pm 10^{-P}), (f_c - .5 bwc) (1 \pm 10^{-P})$$

RADAR

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Trapezoidal Pulse

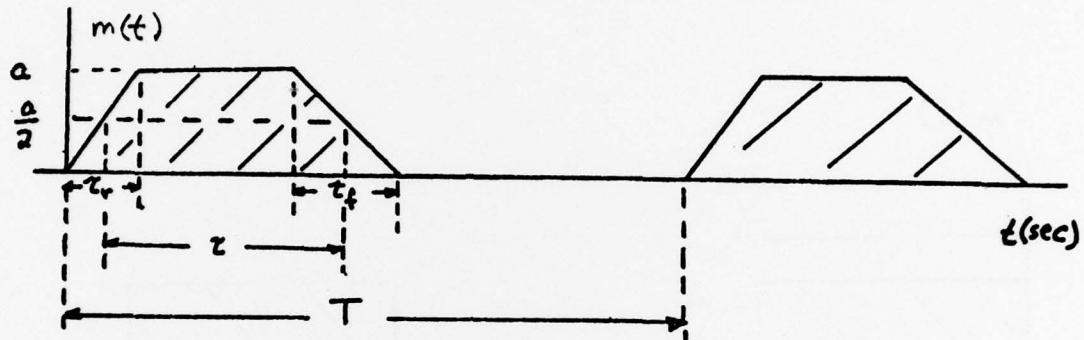
(RADAR, TPZD)

Waveform is:

$$V(t) = m(t) \cos (2\pi f_c t + \phi)$$

$m(t)$ is a Trapezoidal Pulse Train S/C modulation

with unequal rise and fall times:



Required Input Parameters:

$f_L = f_h = \text{carrier frequency } f_c \text{ (Hertz)}$

$P = \frac{a^2}{2} \text{ (Watts)} \quad \left\{ \begin{array}{l} \text{Multiply by } 1/R_L \text{ if } V(t) \text{ is a voltage} \\ \text{and } R_L \text{ if } V(t) \text{ is a current} \end{array} \right\}$

$r_b = \text{bit rate of modulation } \left(r_b = \frac{1}{T} \right) \text{ (Hertz)}$

$\tau = \text{modulation pulse width (between half amplitude levels) (seconds)}$

$\tau_r = \text{modulation pulse rise time (seconds)}$

$\tau_f = \text{modulation pulse fall time (seconds)}$

$$\tau = \alpha \left(\frac{2\tau_r \tau_f}{\tau_r + \tau_f} \right)$$

$$\alpha \leq 3.67$$

$$bwc = \left(\frac{1}{.3\alpha - 1} \right)^{1/3} \frac{2\alpha}{\pi\tau}$$

$$\alpha \geq 3.67$$

$$bwc = \left(\frac{6\alpha}{.3\alpha + 1.9} \right) \frac{1}{\pi\tau}$$

Frequency Table (Hz): $(f_{m1} = 1/\pi\tau, f_{m2} = \alpha f_{m1})$

$$\alpha \leq 3.67$$

$$f_c, f_c \pm f_{m1}, f_c \pm \left(\frac{f_{m1} + f_{m2}}{2} \right),$$

$$f_c \pm f_{m2}, f_c \pm \left(\frac{bwc + f_{m2}}{2} \right), f_c \pm \frac{bwc}{2},$$

$$(f_c + \frac{bwc}{2}) (1 \pm 10^{-P}), (f_c - \frac{bwc}{2}) (1 \pm 10^{-P})$$

$$\alpha \geq 3.67$$

$$f_c, f_c \pm f_{m1}, f_c \pm \left(\frac{bwc}{2} + \frac{f_{m1}}{2} \right),$$

$$f_c \pm \frac{bwc}{2}, (f_c + \frac{bwc}{2}) (1 \pm 10^{-P}),$$

$$(f_c - \frac{bwc}{2}) (1 \pm 10^{-P})$$

RADAR

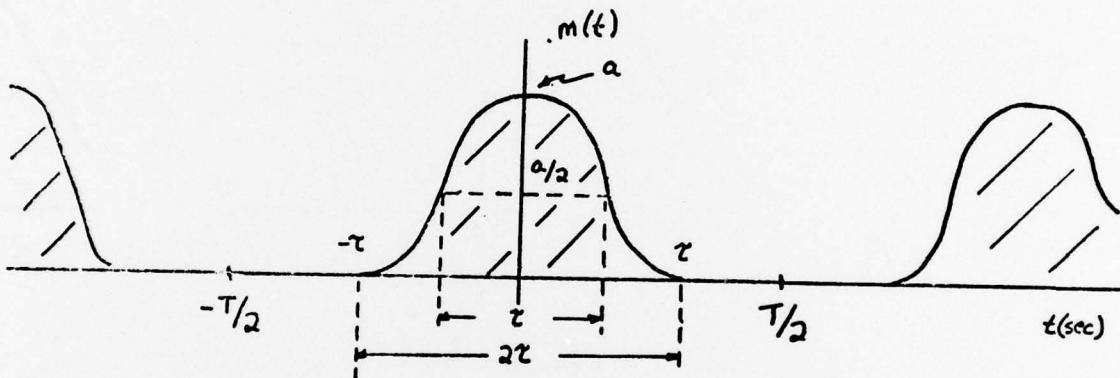
Cosine-Squared Pulse

(RADAR, COSQD)

Waveform is:

$$V(t) = m(t) \cos(2\pi f_c t + \phi)$$

$m(t)$ is a train of pulses of the form:



$$m(t) = a \cos^2 \left(\frac{\pi t}{2\tau} \right) \quad -\tau \leq t \leq \tau$$

Required Input Parameters:

$f_l = f_h = \text{carrier frequency } f_c \text{ (Hertz)}$

$p = \frac{a^2}{2} \text{ (Watts)} \quad \{ \text{Multiply by } 1/R_L \text{ if } V(t) \text{ is a voltage} \}$
 $\{ \text{and } R_L \text{ if } V(t) \text{ is a current} \}$

$r_b = \text{bit rate of modulation } (r_b = \frac{1}{T}) \text{ (Hertz)}$

$\tau = \text{modulation pulse width (between half amplitude levels)}$
 (seconds)

$bwc = .87/\tau \text{ (Hertz)}$

Frequency Table (Hz):

$f_c, f_c \pm .39bwc, f_c \pm .43bwc, f_c \pm .47bwc, f_c \pm .5bwc, (f_c + .5 bwc) (1 \pm 10^{-P}),$

$(f_c - .5 bwc) (1 \pm 10^{-P})$

RADAR

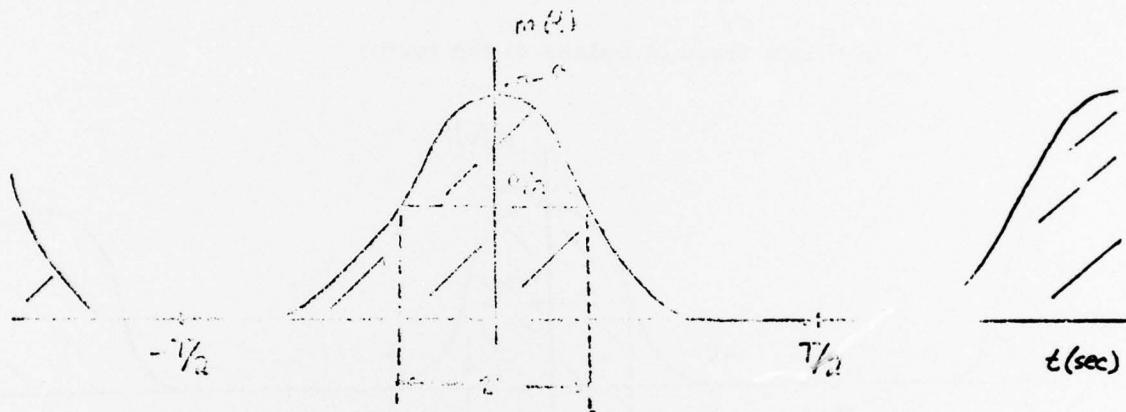
Gaussian Pulse

(RADAR, GA USS)

Waveform is:

$$V(t) = m(t) \cos(2\pi f_c t + \phi)$$

$m(t)$ is a train of pulses of the form:



$$m(t) = a e^{-\left(\frac{2\sqrt{\ln(2)}}{\tau}\right)^2 t^2} \quad -\frac{T}{2} \leq t \leq \frac{T}{2}$$

Required Input Parameters:

$f_l = f_h = \text{carrier frequency } f_c \text{ (Hertz)}$

$P = \frac{a^2}{2} \text{ (Watts)} \quad \left\{ \begin{array}{l} \text{Multiply by } 1/R_L \text{ if } V(t) \text{ is a voltage} \\ \text{and } R_L \text{ if } V(t) \text{ is a current} \end{array} \right\}$

$r_b = \text{bit rate of modulation} \quad \left(r_b = \frac{1}{T}\right) \text{ (Hertz)}$

$\tau = \text{modulation pulse width (between half amplitude levels) (seconds)}$

$$bwc = 1.06/\tau \text{ (Hertz)}$$

Frequency Table (Hz):

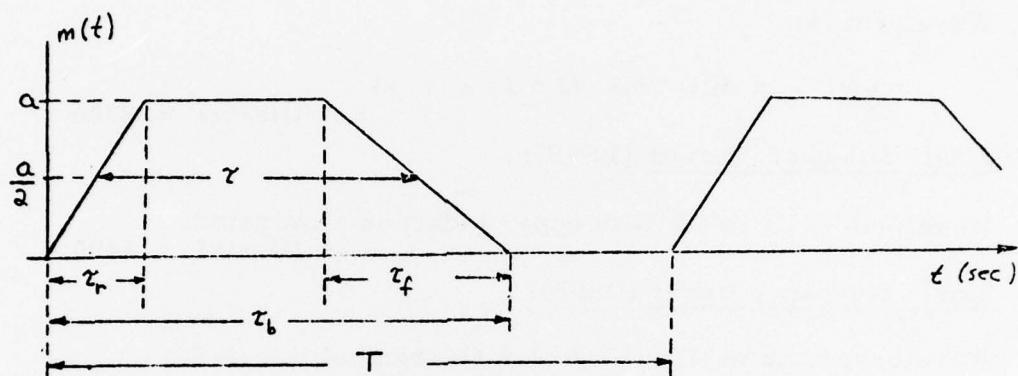
$f_c, f_c \pm .1bwc, f_c \pm .24bwc, f_c \pm .38bwc, f_c \pm .5bwc, (f_c + .5 bwc) (1 \pm 10^{-P}),$

RADAR
Chirp
 (RADAR, CHIRP)

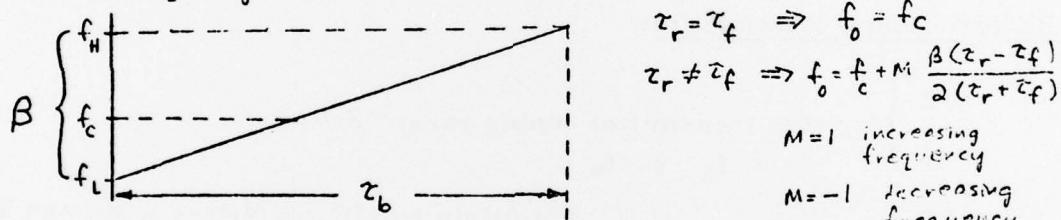
Waveform is:

$$V(t) = m(t) \cos [2\pi (f_0 + \frac{\beta t}{2\tau_b}) t] \\ 0 \leq t \leq \tau_b$$

$m(t)$ is a train of pulses of the form:



frequency deviation is of the form:



$$\tau_r = \tau_f \Rightarrow f_0 = f_c \\ \tau_r \neq \tau_f \Rightarrow f_0 = f_c + M \frac{\beta(\tau_r - \tau_f)}{2(\tau_r + \tau_f)}$$

$M = 1$ increasing frequency

$M = -1$ decreasing frequency

Required Input Parameters:

$f_0 = f_h$ = carrier frequency f_c (Hertz)

$P = \frac{a^2}{2}$ (WATTS) {Multiply by $1/R_L$ if $V(t)$ is a voltage
and R_L if $V(t)$ is a current}

r_b = bit rate of modulation ($r_b = \frac{1}{T}$) (Hertz)

τ = modulation pulse width (between half amplitude levels) (seconds)

τ_r = modulation pulse rise time (seconds)

τ_f = modulation pulse fall time (seconds)

pcr = pulse compression ratio (negative if decreasing frequency)

$$= \beta r_b$$

NOTE: bwc and the entries in EQTRL were not obtained for this model due the complicated nature of the spectrum.

AMPLITUDE MODULATION

VOICE CVOICE

(I) Double Sideband (AM):

Waveform is:

$$V(t) = a (1 + em m(t)) \cos (2\pi f_c t + \phi)$$

bwc (Hertz) = 8800 6400

(II) Double Sideband Suppressed Carrier (DSBSC):

Waveform is:

$$V(t) = a m(t) \cos (2\pi f_c t + \phi)$$

bwc (Hertz) = 8800 6400

(III) Single Sideband, Lower (LSSB):

Waveform is as in (II) with upper sideband eliminated.

bwc (Hertz) = 4400 3200

(IV) Single Sideband, Upper (USSB):

Waveform is as in (II) with lower sideband eliminated.

bwc (Hertz) = 4400 3200

Required Input Parameters:

$$\left. \begin{array}{l} f_l \\ f_h \end{array} \right\} = \text{the transmitter tuning range (Hertz)}$$

$f_l \leq f_c \leq f_h$

$$p = \frac{a^2}{2} \text{ (Watts)} \quad \left. \begin{array}{l} \{\text{Multiply by } 1/R_L \text{ if } V(t) \text{ is a voltage} \\ \text{and } R_L \text{ if } V(t) \text{ is a current} \end{array} \right\}$$

$$em = \text{modulation index } 0 < em \leq 1$$

$$\left. \begin{array}{l} \text{SIG} = \text{VOICE (voice)} \\ \text{CVOICE (clipped voice)} \\ \text{NONVCE (nonvoice)} \end{array} \right\} m(t)$$

$$b = \text{bandwidth of modulation (3dB) if SIG = NONVCE. (Hertz)}$$

If SIG ≠ NONVCE, modulation bandwidth generated

in code and b is not used. Use a 0 placeholder in

this case. (continued)

Frequency Table (Hz):

(I) Double Sideband (AM):

VOICE

$f_c, f_l - 100, f_l - 200, f_l - 1000, f_l - 4000, f_l - 4400, (f_l - 4400) (1 \pm 10^{-P})$
 $f_h + 100, f_h + 200, f_h + 1000, f_h + 4000, f_h + 4400, (f_h + 4400) (1 \pm 10^{-P})$

CVOICE

$f_c, f_l - 350, f_l - 750, f_l - 3200, (f_l - 3200) (1 \pm 10^{-P})$
 $f_h + 350, f_h + 750, f_h + 3200, (f_h + 3200) (1 \pm 10^{-P})$

(II) Double Sideband Suppressed Carrier (DSBSC):

VOICE

$f_l - 100, f_l - 200, f_l - 1000, f_l - 4000, f_l - 4400, (f_l - 4400) (1 \pm 10^{-P})$
 $f_h + 100, f_h + 200, f_h + 1000, f_h + 4000, f_h + 4400, (f_h + 4400) (1 \pm 10^{-P})$

CVOICE

$f_l - 350, f_l - 750, f_l - 3200, (f_l - 3200) (1 \pm 10^{-P})$
 $f_h + 350, f_h + 750, f_h + 3200, (f_h + 3200) (1 \pm 10^{-P})$

(-II) Single Sideband, Lower (LSSB):

VOICE

$f_h, f_l - 100, f_l - 200, f_l - 1000, f_l - 4000, f_l - 4400, (f_l - 4400) (1 \pm 10^{-P}),$
 $f_h (1 \pm 10^{-P})$

$f_h, f_l - 350, f_l - 750, f_l - 3200, (f_l - 3200) (1 \pm 10^{-P}), f_h (1 \pm 10^{-P})$

(IV) Single Sideband, Upper (USSB):

VOICE

$f_l, f_h + 100, f_h + 200, f_h + 1000, f_h + 4000, f_h + 4400, (f_h + 4400) (1 \pm 10^{-P}),$
 $f_l (1 \pm 10^{-P})$

$f_l, f_h + 350, f_h + 750, f_h + 3200, (f_h + 3200) (1 \pm 10^{-P}), f_l (1 \pm 10^{-P})$

FREQUENCY MODULATION

(FM)

Waveform is:

$$V(t) = a \cos[2\pi f_c t + 2\pi \Delta \int_0^t m(\tau) d\tau + \theta]$$

where $m(t)$ is the random modulating signal (VOICE, CLIPPED VOICE, NONVOICE) and θ is a random variable independent of $m(t)$ with uniform distribution over $(0, 2\pi)$

Required Input Parameters:

$f_c = f_h = \text{carrier frequency } f_c \text{ (Hertz)}$

$P = \frac{a^2}{2} \text{ (WATTS)} \quad \begin{cases} \text{Multiply by } 1/R_L \text{ if } V(t) \text{ is a voltage} \\ \text{and } R_L \text{ if } V(t) \text{ is a current} \end{cases}$

$b \approx 6 \text{ dB bandwidth of modulating signal if NONVOICE}$

(Hertz). If VOICE, $b = 712$. If CLIPPED VOICE,

$b = 622$.

$df = \text{maximum frequency deviation from carrier (Hertz)}$

$b_{wc} = 2(df + b)$

Frequency Table (Hz): ($B_{FM} = df + b$)

$f_c, f_c \pm B_{FM}, f_c \pm 1.375B_{FM}, f_c \pm 1.75B_{FM}, f_c \pm 2B_{FM},$

$(f_c + 2B_{FM})(1 \pm 10^{-P}), (f_c - 2B_{FM})(1 \pm 10^{-P})$

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